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DEEP HEAT MINING IN THE AUSTRIAN ALPS – A PRELIMENARY LOOK ON POSSIBILITIES AND LIMITATIONS

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ABSTRACT

Due to intensive hydrocarbon exploration activities in the surrounding basins and partly in the area of the Alpine Thrust Zone, an acceptable density of deep drillings is available. Borehole and seismic data were provided by the OMV Cooperation. Nevertheless geothermal reservoir conditions at the Austroalpine Orogen are still poorly investigated. Already published studies show that the thermal regime in the Eastern Alps is poor to moderate containing temperature gradients between 15° to 30° C / km.

In our study temperature information has been gained from 30 hydrocarbon drillings situated within the Alpine Thrust Zone and nearby regions.

Synthesized temperature profiles based on bottom-hole temperature- (BHT) formation test- (FT) and logging data exhibit decreased thermal conditions heading southwards toward the Northern Calcareous Alps (NCA), strongly influenced by crustal thickening and surface-water inflow.

Due to low density of population within the areas of investigation thermal utilization should focus on electric power generation. Required formation temperatures therefore range between 90°C (ORC-process application) to > 150°C (direct use).

In a subsequent working step, sections of expectable formation-temperatures (“thermal windows”) could preliminary be defined.

Preliminary results suggest a possible thermal use for electric power generation at the Alpine Thrust Zone and its nearby vicinity, although the economical premises are suboptimal.

INTRODUCTION

In Austria, currently installed geothermal capacities reach approximately 61 MW_{th} and 1.2 MW_{el} (Goldbrunner, 2005). Intensive utilization for energetic purposes focuses on sedimentary (=molasse) basins, while the Alpine Orogen itself remains poorly investigated and not exploited yet in a geothermal sense (Figure 1).

So far no studies focused on the hot dry rock (HDR) or EGS method.

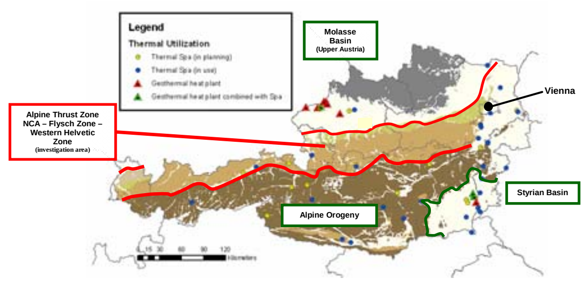

Figure 1 Geographic-tectonic overview of Austria showing the present geothermal utilization

Due to the lack of recent volcanic activities, the thermal regime in Austria has to be considered as poor to moderate, showing heat flow values reaching from 55 mW/m² to approximately 100 mW/m² (Cermak & Hurtig, 1979; Sachsenhofer, 2001). This in term corresponds to thermal gradients between 15 °C/km and 45 °C/km.

Thermal information is mainly basing upon data gained from hydrocarbon exploration.

Our study focuses on the Alpine Thrust Zone north and northeast of the main ridge, where some deep

drillings explored source and reservoir rock quality of thrusted nappes and basement.
The aim of the preliminary study is to explore temperature distribution and to make first conclusions for geothermal energy utilization.

GEOTHERMAL OVERVIEW OF THE AUSTRIAN ALPS

Haenel & Zoth (1973) report a mean heat flow value of approx. 80mW/m² for the European Alpine orogenic belt.
Distribution and magnitude of the thermal regime of the Austrian region implicate typical conditions for a continental crust being influenced by orogenic activities of young folded mountains. In this context the following parameters of influence concerning the present thermal regime have to be taken into consideration:

Alpine thrust zone (Allochthonous Units)

- Hydrodynamic systems (strong influence, local to regional scope)
- Basin depression and sedimentation (moderate to strong influence, regional scope)
- Crustal thickness (moderate to strong influence, regional scope)
- Lithological build-up focusing internal radiogenic heat production (moderate influence, regional scope)
- Transient paleoclimatic signals (weak to moderate influence, regional scope)

Central-Alpine units (~alpine main ridge, Alpine Units, Penninic Units)

- Uplift and denudation (moderate to strong influence, local to regional scope)
- Crustal thickness (strong influence, regional scope)
- Lithological build-up focusing internal radiogenic heat production (moderate to strong influence, regional scope)

Thermal studies have shown that basal heat flow at the crustal basement only varies between 5 and 25mW/m² within the Eastern Alp's region, while minimum values have to be expected beneath the Alpine root reaching maximum Moho depths (Vosteen et al., 2003).
For the Alpine Thrust Zone decreased surface heat flow values (down to approximately 55mW/m²) have been reported (Sachsenhofer, 2001). Significant influences of crustal thickening (thrusting of "cold" sedimentary units) and hydraulic inflow systems on the thermal regime have to be expected there.
Within Central Alpine units heat flux may vary strongly between different tectonic blocks through uplifting and denudation processes and tectonic-block dependent discriminative heat production (Haenel & Zoth, 1973).
Remarkable is a significant influence of the Rheintal Graben system in western Austria (Vorarlberg), where increased heat flow can be assumed reaching 80 to 90mW/m² (Cermak and Hurtig, 1979).

GEOLOGY OF INVESTIGATION AREA

Units of Alpine Thrust Zone reflect mainly sedimentary depositions of Mesozoic and Cenozoic Tethys and Paratethys Ocean.

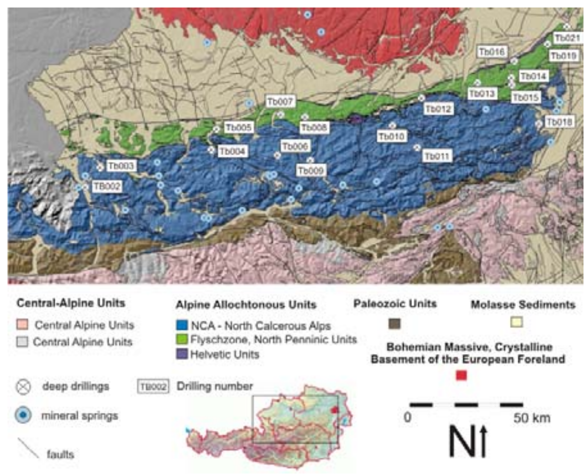

Figure 2 Geologic overview of Austria showing the different tectonic units, (thermal) mineral springs and investigated deep drillings

Alpine Allochthonous Units

Due to collision alpine nappes were oblige to move far north on European foreland causing thrusting and thickening of tectonic units. Summarized from top to base, most important are (Figure 2):
1.) Northern Calcareous Alps (NCA) which comprise mostly Triassic to Jurassic limestones and dolomites. These carbonates were part of a huge platform of Tethys Ocean. Drillings show tectonic thicknesses up to 5 km. Distinct nappes are intercepted only by few and thin sequences built during phases of reduced or no carbonate production and terrigenic sedimentation (gypsum, clay). Permeabilities of limestones can be extreme through strong karstification and tectonic exposure. They represent important reservoirs for drinking water. With depth, limestones tend to loose permabilities significantly through healing processes (Wessely & Wagner, 1993). Drillings show jointed dolomites to be main reservoirs in deep positions within NCA. Layers of Permian gypsum and anhydrites often mark the basement of distinct Calcareous nappes. They comprise an excellent glide planes for thrusting, and important drainage ways for ascending thermal water. Accumulation of thermal mineral springs within units of NCA is remarkable.

2.) NCA are underlain by pelitic, sandy and marly turbidites. Stacked up to 2 km, lower cretaceous to Eocene (sequences) units ("North Penninic Units" or "Flyschzone") represent deposits in very deep sea basin, often associated with bouma cycles. Sediments of Flyschzone have no reservoir quality.
3.) "Helvetic" Units have deepest position of allochthonous units: In eastern parts of Austria these pelitic sequences (clays and marls, below CCD) are developed as a rather thin band at the base of allochthonous units and in some tectonic klippes. In contrast, western parts show a distinct growth and diversity of deposition units as well as a remarkable growth trough duplexing (up to 4 km).

Subalpine Autochthonous Units (Sedimentary Basement)

Authochtonous units, deposited on palaeozoic crystalline (=European Continent). Basement comprises mainly Jurassic fluviatile (delta) sediments (Dogger), carbonates (partly karstified) as well as pelites during Malm (marls and clays). Doggerian fluviatile sandstones are expected to be good reservoirs. Upper Cretaceous strata mark a widespread transgression with glauconitic sandstones during Cenomanian age. Actually the whole Upper Cretaceous series show mainly sandy deposition whose reservoir quality can vary strongly (due to clay minerals).
Conservation of these Mesozoic units depends on erosion processes during Upper Cretaceous and especially Eocene (Wagner, 1998). Upper Eocene terrestric to shallow marine sediments mark the end of the significant erosion process and are the first sediments to cover crystalline basement if Autochthonous Mesozoic Units are missing. They show the beginning of sedimentation of foreland basin in front of the Alpine Orogen. (Malzer et al., 1993). Following sequences can reach up to Pliocene. Due to missing spatial information, knowledge upon autochthonous Mesozoic and Palaeogene units below the Alps is still rather fragmentary.

DATA BACKGROUND - APPROACH

For this preliminary study we used data from the OMV AG. Data on temperature, geology and chemistry of formation waters (Cl^- mg/l, SO_4^{--} mg/l), have been gained from 30 hydrocarbon deep drillings (maximum drilling depths 1500-6000 m) situated within and near the Alpine Thrust Zone. Available thermal raw data cover bottom-hole temperature- (BHT) values, temperature measure-ments in the course of formation testing (FT) (open-hole tests, casing tests) and continuous logs (temperature surveys, cementation testing).
Synthesized temperature profiles were compiled from BHT-values, FT-values and continuous logs allowing a first qualitative look on the Alpine Thrust Zone and its nearby vicinity. Due to poor survey documentation BHT- and FT-temperature values have not be corrected for technical drilling influence. Instead plausibility of FT-temperature values were evaluated obeying the gas contents and possible cooling effects in the course of the formation test due to gas expansion. Beyond only measuring points containing more than one BHT-value have been considered for the elaboration of synthesized temperature profiles.

Chemistries (Cl^- mg/l and SO_4^{--} mg/l) of formation waters have been collected from open-hole test data-sheets (OMV) as well as published hydrochemical analyzes of known surface or near-surface (thermal) mineral springs (Zoetl, Goldbrunner, 1993; Pavuza R., 1990; Schauberger, 1979; Kollmann, 2006).
We favoured analyzing chloride and sulphate content, to take a fist look upon migration paths (especially anhydrite and gypsum rich) within depths and different geological formations. Furthermore these anions were measured in almost all water probes found in literature and in open hole test reports.
Content is used to distinguish between types of (thermal) mineral spring water and formation water.

PRELIMINARY RESULTS

Thermal Regime

Although data correction of BHT- and FT-values could yet not be sufficiently accomplished, significant differences between the thermal conditions at tectonic zones within and nearby to Alpine Thrust Zone can already be outlined (Figure 3):

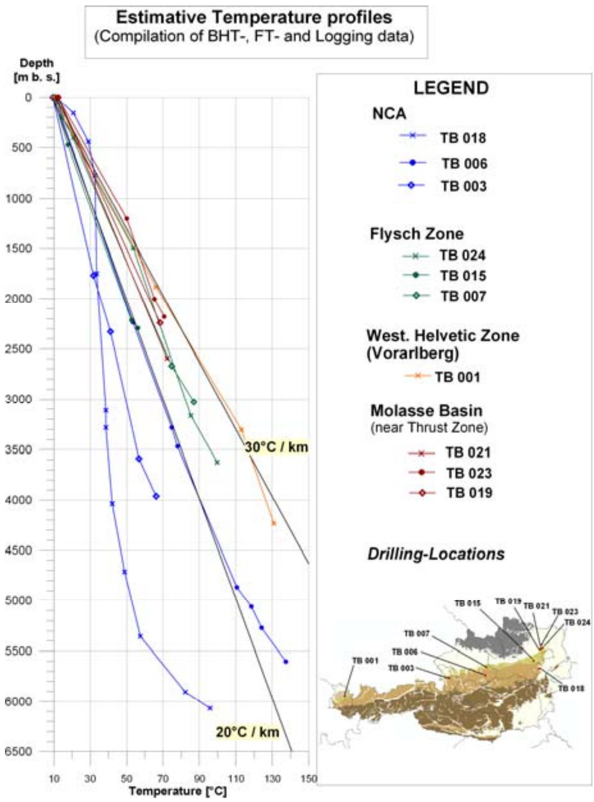

Figure 3 Western plot of synthesized temperature profiles from selected drillings within, or nearby to the Alpine Thrust Zone, the drillings have been allocated to the tectonic zones described in chapter Geology of Investigation Area.

Magnitude of temperature regime (range of overall temperature gradient)

- NCA: 15°C/km (TB018) to 23°C/km (TB006)
- Flysch Zone: 20°C/km (TB015) to 28°C/km
- Western Helvetic Zone: Approx. 30°C/km (TB001)
- Molasse Basin (near Alpine Thrust Zone): 25°C/km (TB021) to 30°C (TB023)

Temperature profiles - Characteristics

- Increased variance of thermal gradients at drillings within the NCA
- Temperature profile of drilling TB018 exhibits very low temperature increase (thermal gradient approx. 5°C/km)
- Low variance of thermal gradients at drillings within the Flysch Zone, Western Helvetic Zone and Molasse Basin nearby to the margin of the Alpine Thrust Zone
- Significant increase of thermal conditions beneath thrusted nappes (NCA, Flysch)
- Slight decrease of thermal gradients heading towards the Alpine Thrust Zone

Based on the compiled synthetic temperature profiles of all analyzed drillings preliminary sections of expectable reservoir temperatures – now called "thermal windows" - have been defined (Figure 3). To improve the data background at the Western Helvetic Zone (Vorarlberg), published data gained from the drilling "Sulzberg" have been added (Starck, 1989).

According to geothermal utilization for electric power generation, three isothermal-depths are of special interest:

- 90°C isotherm: Appliance Organic-Rankine-Cycle (ORC-) methods
- 120°C isotherm: Appliance of Kalina-process
- 150°C isotherm: direct electric power generation

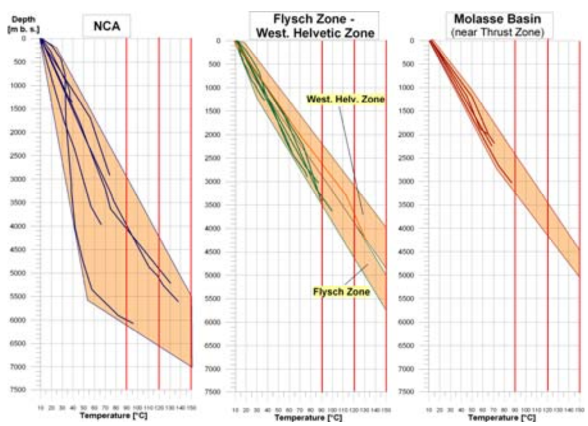

Figure 4 Thermal Windows – sections of expectable reservoir temperatures according to tectonic units within and nearby to the Alpine thrust zone, taking into account thermal requirements of electric heat production

Hydrologic Conditions

In order to explore possible migration (exfiltration) and infiltration paths we compared (thermal) mineral spring waters with formation waters.

We were able to distinguish between 6 main types regarding their content of Cl^- mg/l and SO_4^{--} mg/l:

1.) Basal formation water of Subalpine Autochthonous Units with moderate content of Cl^- (~ 2000 – 11000 mg/l,) and low content of SO_4^{--} (~ < 500 mg/l)
2.) Basal formation water of Subalpine Autochthonous Units with high content of Cl^- (much higher than 10.000 mg/l and low content of SO_4^{--})
3.) (Ascending) formation water within Alpine Allochthonous Units with moderate content of Cl^- and high content of SO_4^{--}

4.) (Thermal) mineral spring water with moderate content of Cl^- and high content of SO_4^{--} (> ~500 mg/l).
5.) (weak overtemperated) mineral spring water with low content of Cl^- (much lower than 2000 mg/l) and high content of SO_4^{--}.
6.) (Thermal) mineral spring water with low content of both anions.

DICUSSION

Complex data interpretation

Northern Calcareous Alps (NCA)

Due to widespread karstified and jointed surface rocks of NCA, surface water can infiltrate very easy into underground and supply aquifers. Investigations in some parts of NCA show remarkable deficits in mass balance between infiltration water and exfiltration of nearby springs (pers. com. Pavuza R, Plan L., 2006).
We suppose that some water is forced to drain fast into deeper formations and cool formation.
Low geothermal gradients and significant scattering of synthesized temperature profiles (between 15°C/km and 23°C, Figure 3 and 4) suggest influence of hydrodynamic systems within NCA. Regarding drilling TB018 the impact of “cold” surface-water inflow is evident showing almost steady thermal conditions down to depths of more than 4500 m below surface (Wessely, 1983). In addition abnormal low chloride anions of TB 018 indicate surface-near water. Rainfall coupled earthquake activity (1 to 4 km depth) along major faults in NCA show possibilities of fast influxing precipitation waters into deep underground too (Hainzl et al., 2006.). Also high content of measured radon gases of several NCA springs advice at least deep infiltration to major depth (Zötl & Goldbrunner, 1993).

Occurrence of (thermal) mineral springs within units of NCA is remarkable (Figure 2) and indicates hydrodynamic systems.
In accordance with data published so far we suggest that raised content of sulfate in (thermal) mineral springs show contact with Upper Permian and Triassic gypsum and anhydrite rocks. These rocks often built tectonic glide planes between distinct tectonic nappes. Rapid solution processes can be responsible for extreme permeabilities and create very effective ways for thermal mineral water to ascend quickly, loosing heat only marginally (Pavuza, 1990).
Applying our 6 type model we can find at least two hydrodynamic systems within the Alpine Thrust Zone (figure 5):
First, a surface near system with rather cool temperatures (type 5 waters). These waters could not drain very deep into underground but were able to raise content of SO_4^{--} already (Pavuza, 1990).
The second system comprises a deep hydrodynamic system: Waters who were able to infiltrate to deep units (Subalpine Autochthonous Units) could raise temperature and content of Cl^-. We supposed that Cl^- content is enriched in basal sediments (e.g. Eocene and Cretaceous sandstones). Basal waters of Subalpine Autochthonous Units never show high content of sulphate but at least moderate content of chloride (type 1 waters). There, hot water is forced to ascend and use preferentially glide planes of NCA nappes where they solve and raise sulphate (type 3 waters). Then, fed springs show high values of SO_4^{--} and Cl^- (type 4 waters).

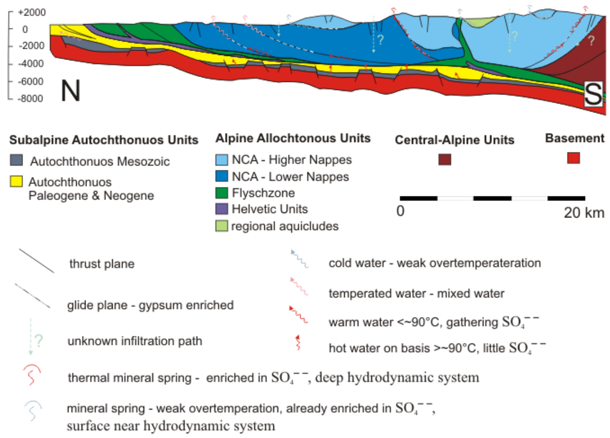

Figure 5 Cross Section through Alpine Thrust Zone, showing tectonic units and hydrodynamic systems

Flysch Zone

Compared to thermal conditions at the NCA, synthesized temperature profiles of drillings within the Flysch Zone show slightly increased temperature gradients in the range of 20°C/km to 28°C/km, while scattering of profiles is significantly reduced. Coherency to missing distinctive hydrodynamic systems within the Flysch nappes is suggested.
Sealing quality of whole Flysch units is shown at drilling TB 018. Below these units, a clear rise in geothermal gradient is associated with a significant rise in content of Cl^-. Here, a hydrostatic formation water lense is supposed (water type 2).
Assumable depth of crystalline basement, respectively crustal thickness vitally influences the magnitude of the overall thermal gradient. As observed before (NCA), thermal conditions change beneath thrusted nappes indicating again increased temperature gradients. Possible reasons for this significant change of the thermal regime are local hydrodynamic systems (related to slide planes), as well as possible heat storage within the overburden autochthon tectonic units. Further investigations shall provide more clarify coherences.

Western Helvetic Units (Vorarlberg)
The synthesized temperature profile of drilling TB001 shows a thermal overall gradient of approximately 30°C/km slightly decreasing at the greater depths. Formation-tests at TB001, done by OMV AG, yield absence of extensive aquifers within Helvetic units. It can be assumed, that the resulting thermal regime is influenced by the nearby Rheintal-Graben regime (increase) as well as by thrusting of "cold" sediments (decrease).

Molasse Basin (near Alpine Thrust Zone)
Temperature profiles of drillings nearby to the Alpine Thrust zone exhibit thermal conditions comparable to those observed within the Flysch Zone. Assumably due to lowering crustal thickness (heading northwards) and lacking thrusting, slightly increased temperature gradients between 25°C/km to 30°C/km can be observed.

Strength &Limitation

Due to insufficient survey documentation most BHT values could not be corrected for technical influence yet. Therefore knowledge about drilling- and flush circulation duration, as well as the time period since circulation has stopped is crucial. Unfortunately, circulation time remains widely unknown due to insufficient documentation. In almost all observed cases continuous temperature logs also show strong technical drilling influence as a consequence of too low waiting periods between circulation suspension and start of logging. Additionally most logs have been carried out in cased boreholes, where formation water inflow is inhibited. Evidence for eminent drilling influence is yield by elevated zero – depth temperatures (20 to 40°C) and too moderate thermal gradients. Temperature measurements in the course of hydraulic formation tests in many studied cases provide the most reliable formation-temperature information. Remarkable disturbing influence occurs in case of significant natural gas appearance (cooling effects as a consequence of gas expansion). It has to be pointed out, that all assumptions concerning the physical thermal regime made are quite estimative at the current stage of progress.
Due to a very clear rise in occurrence of (thermal) mineral springs within NCA, almost only spring data from these tectonic units were taken into account.
Because of availability of Cl^{-} in mg/l and SO_4^{--} mg/l in almost all described sample data, only these anions considered. For supposed influence of gypsum and anhydrite on waters, SO_4^{--} content represent a good marker. Furthermore, content of Cl^{-} and SO_4^{--} is supposed to be well comparable in these rather unsaturated (thermal) mineral spring and formation waters due to no significant difference in solubility in dependency of temperature and pressure. Because of data taken from literature and reports we are not able to make statements on exact sampling. Temperature information is sometimes missing within data and could therefore not always be considered and compared. Finally more but undiscovered (thermal) mineral springs could occur within investigation area.

CONCLUSION

Referring to possible geothermal utilization by terms of hydrothermal- (naturally existing tempered aquifers) and EGS- methods, we are able to draw the following conclusions at the present stage of our studies:

1.) Due to low density of population within the chosen investigation area (Alpine Thrust Zone and close vicinity) energetic geothermal use shall be focused on electric power generation. Required minimum reservoir-temperatures are therefore ranging from 90°C (ORC) to 150°C (direct use).
2.) Due to increased crustal thickness required minimum-reservoir depths vary from approx. 2500 m below surface at the northern margin of the Alpine Thrust zone to more than 3500 m below surface within the NCA.
3.) Synthesized temperature profiles of drillings within the Alpine Thrust Zone (NCA, Flysch Zone, and Western Helvetic Zone) exhibit a clear rise of formation-temperatures of Subalpine Autochthonous Units beneath the thrusted nappes. A thermal barrier leading to heat-storage within the Autochthonous Units may be assumed leading to more favorable thermal conditions.
4.) Strong influence of hydrodynamic inflow-systems (surface waters) is superposing thermal regime of the NCA, producing significant decrease of thermal regimes at local scope. Therefore a so called thermal window (Figure 4) according to reservoir temperatures of 90°C (utilization of ORC – processes) strongly varies between 3500 and 6000 m below surface.
5.) Hydrological and hydrochemical data imply two relevant hydrodynamic systems within the NCA – Zone. Especially at slide planes within and at basis of NCA nappes, migration paths for water outflow assumably exist.
6.) In general geothermal utilization is economically possible within the Alpine Thrust Zone. However decreased thermal gradients are reducing utilizable

reservoir volumes. Assuming a economically limited maximum drilling length of 6000 to 7000 m, exploiting geothermal energy is not possible in NCA. But sedimentary rocks of Subalpine Autochthonous Units which were subducted to major depths (probably much more than 9000 m below surface) may become a future target if drilling costs generally may decrease.

7.) Due to remarkable positive influence of the Rheintal Graben system (reduced crustal thickness) more favorable thermal conditions can be assumed at Western Helvetic Zone, leading to increased thermal gradients up to 32°C/km and respectively to required possible reservoir depths of less than 3000 m (ORC-process application).

More precise temperature progression and low scale thermal analyzes will be able after the execution of detailed numerical thermal modeling (1D, 2D). Modeling will be done as all relevant petrophysical- and hydraulic formation parameters will be extracted from the data sheets provided by the OMV. Additional acquisition-work has to be done concerning survey documentation (geophysical borehole logging, formation tests) to improve BHT- and FT- data correction. This will in turn lead to more precise synthesized temperature profiles.
For more comprehensive reservoir studies and better confining of exploitative reservoirs within the Alpine Thrust Zone formation-parameters have to be statistically analyzed and added to the already estimated "thermal window".

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